ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-THYA01

PERFORMANCE TESTING OF FRIB EARLY SERIES CRYOMODULES*

J.T. Popielarski†, C. Compton, A. Ganshyn, W. Hartung, D. Luo, S.J. Miller, D.G. Morris, P.N. Ostroumov, L. Popielarski, K. Saito, S. Shanab, S. Stark, T. Xu, S. Zhao, Z. Zheng
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

Construction of a new accelerator for nuclear physics research, the Facility for Rare Isotope Beams (FRIB), is underway at Michigan State University (MSU). The FRIB linac will use superconducting resonators operating at a temperature of 2 K to accelerate ions to 200 MeV per nucleon. The linac requires 104 quarter wave resonators (80.5 MHz, β = 0.041 and 0.085) and 220 half wave resonators (322 MHz, β = 0.29 and 0.53), all made from sheet Nb. Production resonators are being fabricated by cavity vendors; the resonators are etched, rinsed, and tested in MSU's certification test facility. Cavity certification testing is done before the installation of the high-power input coupler and tuner. After certification and cryomodule assembly, the resonators are tested in the cryomodule before installation into the FRIB tunnel. The cryomodule test goals are to verify integrated operation of the resonators, RF couplers, tuners, RF controls, and superconducting solenoids. To date, 12 out of 46 cryomodules have been completed, and 9 have been certified. Cavity and cryomodule certification test results are presented in this paper.

FRIB CAVITIES

The FRIB linac will use 2 types of quarter wave resonators (QWRs), and 2 types of half wave resonators (HWRs). Drawings of the production cavities are shown in Figure 1; design parameters are given in Table 1. Prior to cavity production, all cavity designs were validated with pre-production cavities. The goal for Dewar certification testing of production cavities is to reach an accelerating gradient (E_a) 20% higher than the cryomodule performance goal, with the same intrinsic quality factor (Q_0).

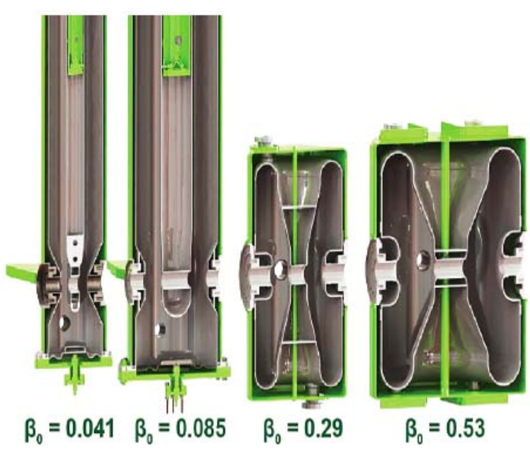

Figure 1: Isometric sectional views of FRIB production cavities.

*Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661
†popielar@frib.msu.edu

Table 1: FRIB Production Cavity Parameters

Cavity Type	QWR	QWR	HWR	HWR
β_0	0.041	0.085	0.29	0.53
f (MHz)	80.5	80.5	322	322
Accelerating voltage (MV)	0.81	1.78	2.09	3.70
E_a (MV/m)	5.1	5.6	7.7	7.4
Peak E field E_p (MV/m)	30.8	33.4	33.3	26.5
Peak B field B_p (mT)	54.6	68.9	59.6	63.2
Q_0 (VTA)	1.4E9	2.0E9	6.7E9	9.2E9
# of cavities/cryomodule	4	8	6	8
Total Dynamic load to cryoplant (2 K)	7.3	34.8	22.8	65.2
Control bandwith (Hz)	40	40	52	30
Maximum RF power (kW)	0.7	2.5	2.8	5.0
# of cavities needed	12	92	72	148
# of cavities certified	16	69	68	17
# of cryomodules needed	3	11	12	18
# of cryomodules certified	3	5	0	1

CAVITY PRODUCTION AND TESTING

As of July 2017, 240 cavities have been received out of 324 cavities needed for the FRIB linac; 208 cavities have been certified for installation in cryomodules. The remaining cavities will be received by the middle of 2018. Approximately 10% of the cavities were returned to the vendor before Dewar testing due to issues identified during acceptance checking (welds, dimensions, threads, etc.). More detailed cavity production information can be found in a separate paper [1].

After acceptance, production cavities are cleaned, etched (buffered chemical polishing, BCP), hydrogen degassed, and high-pressure water rinsed at MSU [1]. These steps are carried out in the FRIB SRF High Bay [2].

All cavities undergo a Dewar certification test before they are installed in a cryomodule. Up to 5 cavities can be Dewar tested per week. Less than 20% of the cavities require rework after the first Dewar test. Certified cavities are installed into cryomodules at MSU [3].

Dewar Test Procedures and Certification Requirements

Resonators are delivered with their helium jacket. The Dewar test is done in such a way as to approximate the cryomodule environment, with liquid helium in the jacket and the Dewar under vacuum (in contrast to the more customary Dewar dunk test of an unjacketed cavity). As seen in Figure 2, we use an insert with a helium reservoir, which provides a larger volume of helium for pumping to 2 K. The insert is prepared and installed into the Dewar the evening before the test begins. After the morning cooldown, testing is done at 4.3 K, along with thorough conditioning of multipacting barriers. Typically the 4.3 K testing

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-THYA01

Figure 2: Insert for a Dewar test with a jacketed β = 0.085 QWR attached. The helium reservoir can be seen above the cavity.

takes 1 to 4 hours. After 4.3 K testing, we pump down and test at ~2 K, which typically takes < 2 hours. We use ~50 W of forward power for high-field testing and conditioning. The cavity is then warmed up and removed from the Dewar, typically during the evening shift after the test. The Dewar warms up within one day and can be used every other day. We are able to do 1 cavity test per day using two Dewars, although a third Dewar pit has been prepared and commissioned.

Table 2 shows the Dewar test certification requirements for FRIB cavities. Additional measurements during the Dewar test include the Lorentz detuning coefficient, X-rays, and cavity stiffness (*df*/*dP*, with *f* = cavity frequency, *P* = helium bath pressure), though there is no explicit certification requirement for them. Another important part of the Dewar test is to verify leak tightness of the cavity and helium vessel at 2 K. If a leak into the insulating space is observed, we repeat the Dewar test after repairing any leaks on the insert cryogenic plumbing to double-check the integrity of the helium jacket.

Dewar Test Results

Figure 3 shows the performance of cavities which passed the certification Dewar test. The production cavities have a comfortable performance margin for both gradient and Q_0, except for the β = 0.085 QWRs, as will be discussed below. The gradient limitation is not typically quench-related. The "high-field *Q*-slope" is observed at gradients above the FRIB design goal, and is seen with or without X-rays. Reworks due to field emission have been infrequent; high X-rays are not typically observed at the FRIB design gradient.

Table 2: Certification requirements for Dewar testing of FRIB cavities at 2 K (P_{cav} = cavity pressure; $Q_{ext,2}$ = pickup coupling strength).

β_0	**0.041 0.**	**085**	**0.29**	**0.53**
Q_0	$> 1.4\times10^9$	$> 2.0\times10^9$	$> 6.7\times10^9$	$> 9.2\times10^9$
E_a (MV/m)	> 6.1	> 6.7	> 9.2	> 8.9
P_{cav} (torr)	$< 1\times10^{-8}$	$< 1\times10^{-8}$	$< 1\times10^{-8}$	$< 1\times10^{-8}$
$Q_{ext,2}$	7.8×10^9 to 7.8×10^{10}	4.4×10^{10} to 4.4×10^{11}	9.4×10^{10} to 9.4×10^{11}	2.8×10^{11} to 2.8×10^{12}
f (MHz)	80.506 ± 0.010	80.504 ± 0.010	322.088 ± 0.025	322.070 ± 0.040

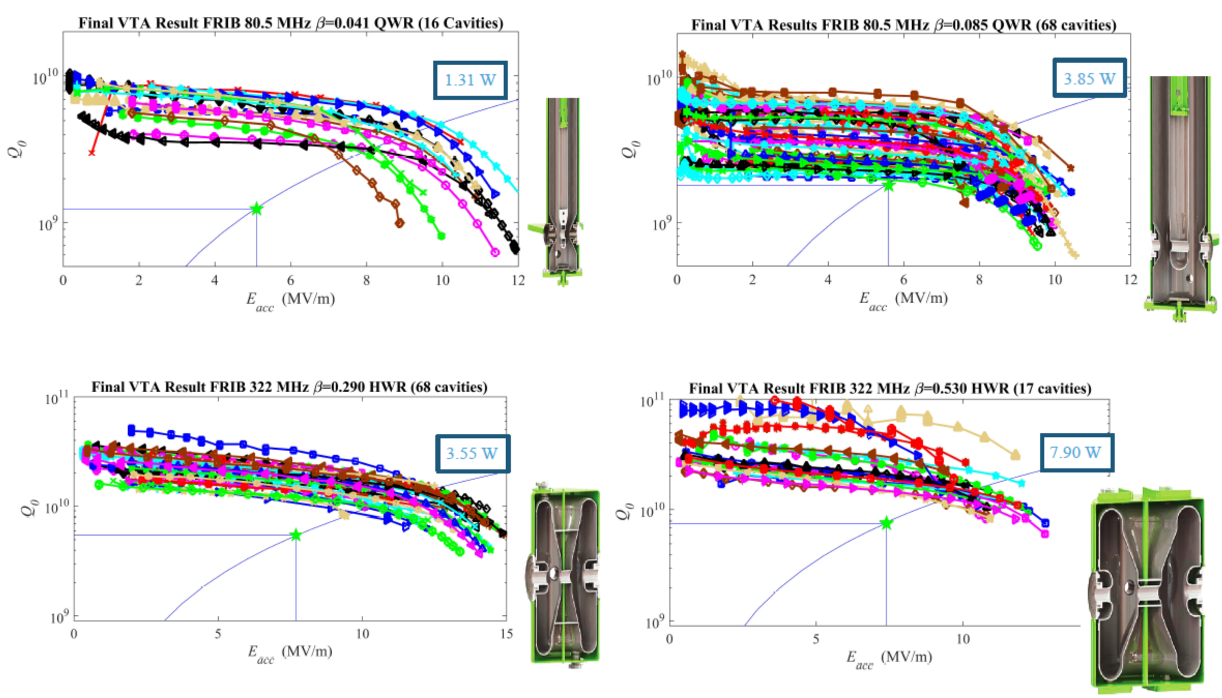

Figure 3: Dewar certification test results at 2 K: final test before installation onto the cold mass.

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-THYA01

Indium Seal Issue: β = 0.085 QWRs

Early production FRIB β = 0.085 QWRs had a large spread in Q_0, as seen in Figure 3 (top right). The Q_0 was lower than expected from pre-production cavities and ReA3 cavities [4, 5]. The low Q_0 values led to a higher incidence of rework and retesting for the β = 0.085 cavities.

The FRIB QWR design makes use of a Nb tuning plate, with a bottom flange to provide the vacuum seal and RF seal. Indium wire is used to seal the joints between the tuning plate, cavity outer conductor, and bottom flange.

Pre-production cavities and ReA3 cavities underwent a low-temperature bake prior to Dewar testing. The bottom flange bolts were retorqued after the bake-out. The bake-out and retorquing steps were omitted from the production cavity preparation steps.

A small-scale investigation was undertaken in parallel with cavity production in the hope of mitigating the low Q_0 values. A fruitful step in the investigation was to retest a low-Q_0 cavity after retorquing the bottom flange bolts. After retorquing to the same torque as was originally used in the clean room, the Dewar test showed a significantly improved Q_0 (by a factor of ~3).

Additional tests showed that retorquing the bottom flange before the Dewar test results in higher average Q_0 and smaller performance spread. Hence we adjusted our procedures to add a retorque step prior to the Dewar test but at least 3 hours after the original torquing and pump-down in the clean room. As shown in Figure 4, this retorquing step produced a higher average Q_0.

The underlying explanation for these observations is likely associated with flow of the indium after the first torquing step. We note that retightening of the seal is a common practice for indium; for example, the vacuum procedures for the CEBAF superconducting linac include multiple indium seal retorquing steps to mitigate creep [6]. We found that the original torque on the bolts decreased by approximately 50% over time, even without changing the vacuum load. Understanding this, we still had concerns about thermal cycling and possible long-term degradation of the indium joint. In one cavity that was retorqued before the Dewar test, we warmed up, cooled back down, and did another Dewar test to check for degradation due to a thermal cycle (see Figure 5). The second Dewar test was done after 1 week at room temperature; a third Dewar test was done after 1 month at room temperature. No additional torquing was done between the first, second, and third Dewar test. As seen in Figure 5, there was no degradation in Q_0 due to thermal cycling.

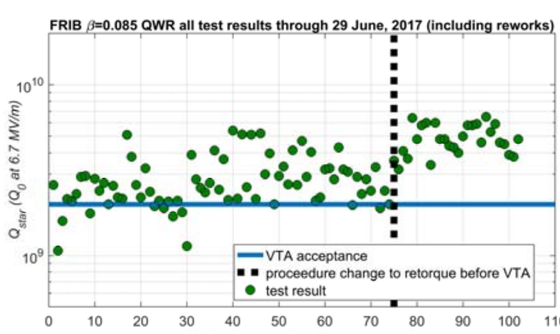

Figure 4: Measured Q_0 values before and after the addition of a retorquing step prior to the Dewar test.

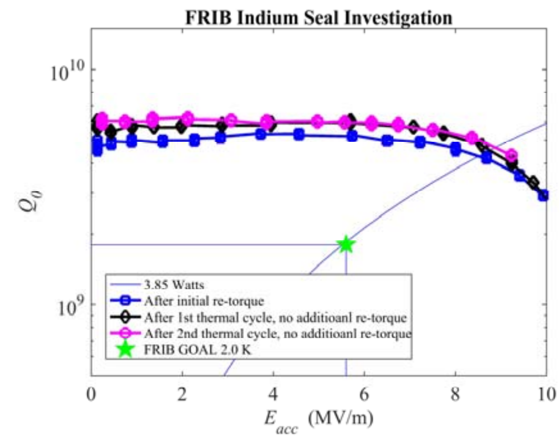

Figure 5: Measured cavity performance with retorquing and subsequent thermal cycling.

Fortunately, the cryomodule assembly procedures included a bottom flange retorquing step for all production QWRs after the cavity is installed onto the cold mass in the clean room. Hence we do not expect to see a low Q_0 due to the indium seal in the cryomodule tests or in the linac. We confirmed during the cryomodule tests that the β = 0.085 QWR dynamic loads are smaller than what would be expected based on the Dewar tests. Thus we do not anticipate that the indium seals will adversely impact the cavity performance in the linac.

CRYOMODULE TESTING

FRIB cryomodules are tested before installation into the tunnel; 9 cryomodule tests have been completed so far.

Cryomodule Test Procedure

Figure 6 shows the test procedure. During cavity testing, we check the cavity frequency and bandwidth; we do a field level calibration; we measure X-ray production as a function of field and check for degradation in cavity performance relative to the Dewar test; and we measure the forward power as a function of field in self-excited loop mode and with the frequency, amplitude, and phase locked to the reference. Additionally, we test the superconducting

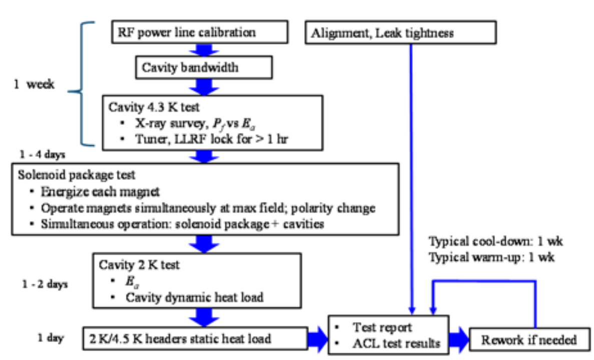

Figure 6: FRIB cryomodule test procedure flowchart.

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-THYA01

solenoid package (solenoid and two pairs of dipoles for beam steering); we measure the heat load (4 K solenoid header; static and dynamic load to 2 K); we check leak tightness of vacuum spaces; and we monitor the alignment during the cool-down and warm-up.

Static and dynamic loads are inferred from measurements of one of the following: (i) rate of increase in the helium bath pressure as a function of time with the supply and return valves closed; (ii) helium return gas flow rate with the return valve open; (iii) rate of decrease in the liquid helium level with the supply valve closed. The load from a resistive heater is used to calibrate the measurements. In first-article cryomodule tests, the dynamic load is measured for all of the cavities and couplers.

Cryomodule Testing Infrastructure

We have 2 bunkers for cryomodule testing, one in the FRIB SRF High Bay and the other in the reaccelerator area of the East High Bay.

SRF High Bay Bunker This bunker, shown in Figure 7, is fully equipped for FRIB cryomodule testing, with a dedicated 2 K/4.3 K cryogenic distribution system. Two side-by-side bays were constructed, but only one bay has been commissioned so far (due to limited funds and limited personnel resources). There are 2 RF systems on the top of the bunker, allowing us to test 2 cavities simultaneously and switch between cavities fairly quickly without having to open the bunker. The same cryogenic plant is used for cryomodule testing and Dewar testing of cavities, but both can be done at the same time.

So far, the SRF High Bay bunker has been used only for HWR cryomodule testing. The test of the first β = 0.53 HWR cryomodule (SCM501) has been completed; the test of the first β = 0.29 HWR cryomodule (SCM201) is in progress.

Figure 7: SRF High Bay bunker: exterior (left) and interior (right).


Figure 8: ReA6 bunker: during (left) and after (right) cryomodule installation.

ReA6 Bunker This bunker, shown in Figure 8, is located in the East High Bay of NSCL (National Superconducting Cyclotron Laboratory), adjacent to the SRF High Bay building. The bunker will ultimately be used for the energy upgrade of the NSCL reaccelerator (ReA6). The cryogenic distribution line and U-tube connections are of the same design as are being installed in the FRIB linac tunnel. Two RF systems are used, but only 2 RF transmission lines are installed through the bunker wall, so switching between cavities must be done inside the bunker. The 900 W helium refrigerator is shared with ReA operations. This system is basically a 4.3 K system, with no closed circuit for 2 K operation, so the helium gas is not recovered when we pump to 2 K.

The ReA6 bunker has been operational since March 2015. So far we have tested 8 QWR cryomodules in this bunker, including one prototype cryomodule. The cool-down of the ninth cryomodule QWR is underway. Upgrades to the ReA6 bunker are planned for HWR cryomodule testing.

CRYOMODULE TEST RESULTS

First $\beta = 0.085$ Cryomodule: SCM801

This was the first full FRIB QWR cryomodule. As shown in Figure 9, we achieved $E_a > 6$ MV/m (goal: ≥ 5.6 MV/m) with $P_f \leq 1.1$ kW (goal: ≤ 2.5 kW) at 4.3 K for all 8 cavities in the bunker test. The measured bandwidth was 31 ± 8 Hz averaged over 8 cavities, which is compatible with the FRIB goal (40 Hz). The FRIB 2 K dynamic load requirement is ≤ 3.85 W/cavity (including the estimated RF coupler load of 0.25 W), corresponding to $Q_0 \geq 1.8 \times 10^9$. The measured dynamic loss at 2 K was 2.8 W/cavity, corresponding to $Q_0 = 2.5 \times 10^9$ on average, so that there is ~40% margin in dynamic load. No Q-degradation was observed relative to the Dewar certification tests; the X-rays were lower in the cryomodule test than in the Dewar tests.

All of the couplers and tuners worked well, without any issues. All of the cavities were locked within the RF amplitude and phase spec at 4.3 K for > 1 hour, and the low-level RF control worked very well. Table 3 summarizes the cavity RF performance parameters measured in the bunker test. On average, the RF amplitude and phase control are about 1 order of magnitude better than the FRIB goals.

The cryogenic system was very stable throughout the bunker test. The measured static heat loads were 28.8 W (goal: 36 W) for the 2 K cavity circuit and 23.7 W (goal: 22.6 W) for the 4.3 K solenoid circuit. The latter value is considered to be acceptable, given the estimated uncertainty in the measured value (10 %).

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-THYA01

Table 3: Cavity RF Performance and Control for SCM801 (pk-pk: peak-to-peak; rms: root-mean-square)

Cavity Position	Amplitude		Phase		BW (Hz)	Forward Power			Forward Phase		Detune	
	pk-pk (%)	rms (%)	pk-pk (deg)	rms (deg)		nom (W)	ave (W)	max (W)	pk-pk (deg)	rms (deg)	pk-pk (Hz)	rms (Hz)
1	0.07	0.01	0.08	0.01	20.2	487	1161	1280	29	1.5	6.5	0.3
2	0.64	0.05	0.58	0.07	38.6	931	1005	1552	68	7.7	29.2	3.3
3	0.08	0.01	0.09	0.01	43.6	1052	1163	1274	28	1.5	13.4	0.7
4	0.09	0.01	0.25	0.03	37	893	1076	1318	28	2.9	11.5	1.2
5	0.26	0.01	0.53	0.07	24.8	598	488	858	72	7.9	19.6	2.2
6	0.09	0.01	0.09	0.01	27.1	654	650	681	9	1.4	2.7	0.4
7	0.06	0.01	0.31	0.02	26.5	639	702	835	23	2.1	6.8	0.6
8	0.14	0.01	0.32	0.04	26.3	634	645	924	49	5.7	14.2	1.7
Average	**0.18 ± 0.20**	**0.02 ± 0.01**	**0.28 ± 0.20**	**0.03 ± 0.03**	**30.5 ± 8.1**	**736 ± 196**	**861 ± 268**	**1090 ± 305**	**38 ± 22**	**3.8 ± 2.8**	**13.0 ± 8.4**	**1.3 ± 1.0**
Spec	**2.00**	**0.25**	**2.00**	**0.25**	**40.0**	**1088**	**1305**	**2500**	**90**	**3.75**	**< 20**	**< 2.25**

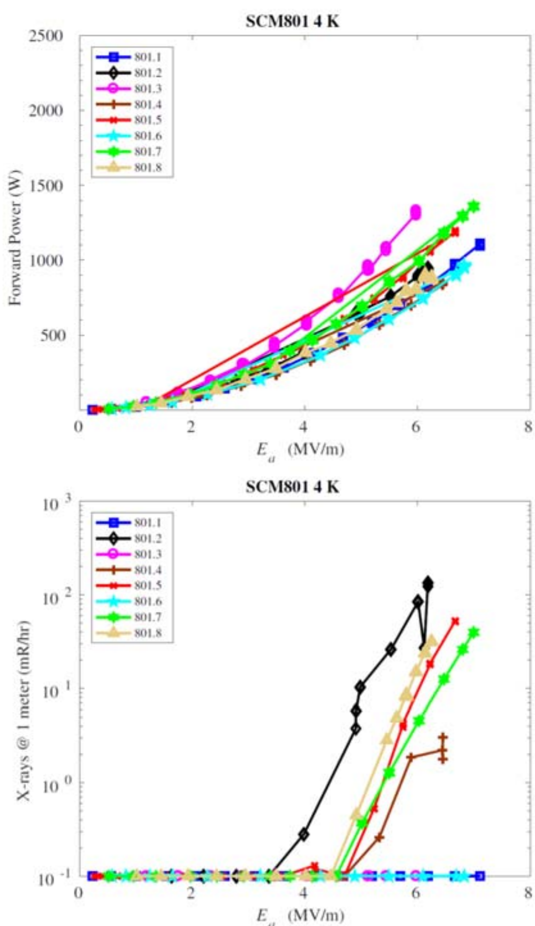

Figure 9: RF and radiation measurements at 4.3 K on the first β = 0.085 cryomodule (SCM801).

Production β = 0.041 Cryomodules

Three β = 0.041 cryomodules (SCM401, SCM402, SCM403) have been tested. As seen in Figure 10, no steady-state X-rays were observed in the RF tests other than some transient spikes which were conditioned away easily. All cavities were locked in amplitude, phase, and frequency within the FRIB requirements for ≥1 hour at 4.3 K. The 2 K dynamic heat load measurement confirmed that the heat load is well below the design goal.

Production β = 0.085 Cryomodules

Three accelerating β = 0.085 cryomodules (SCM802, SCM803, and SCM804) were produced after the first article cryomodule. Figure 11 shows the high-power RF testing results.

An additional matching cryomodule (SCM901) was fabricated and tested. It includes four β = 0.085 QWRs, but has no solenoid packages. Figure 12 shows cavity test results for the matching cryomodule.

All of the cavities were locked in amplitude, phase, and frequency within the FRIB requirements for ≥1 hour at 4.3 K. The 2 K dynamic heat load measurements confirm that the heat load is less than the design value. No cavity performance degradation was observed relative to the Dewar certification tests.

First β = 0.53 Cryomodule: SCM501

This was the first full FRIB HWR cryomodule. The cold mass is shown in Figure 13. SCM501 provided the first opportunity to test the pneumatic tuner [7] in a cryomodule. Figure 14 shows the tuner design, which was developed at ANL.

In the cryomodule test, all cavities reached fields above the FRIB requirement of E_a = 7.4 MV/m, with forward power $P_f \leq 3.5$ kW at 4.3 K, well within the FRIB requirement ($P_f < 5$ kW).

Pre-production RF input couplers were used for SCM501. We observed multipacting in the couplers which was difficult to condition. This led us to develop a system to bias the coupler inner conductor [8]. We found that we were able to suppress the coupler multipacting barriers effectively with a bias of −1 kV. In the next cryomodules, a new coupler design for reduced multipacting will be used [9].

More information about the fabrication, testing, and performance results for SCM501 can be found elsewhere in these proceedings [10].

First β = 0.29 Cryomodule: SCM201

Testing of the first β = 0.29 HWR cryomodule is currently underway in the SRF High Bay bunker. This cryomodule is the first to use the new coupler design [9]. All

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-THYA01

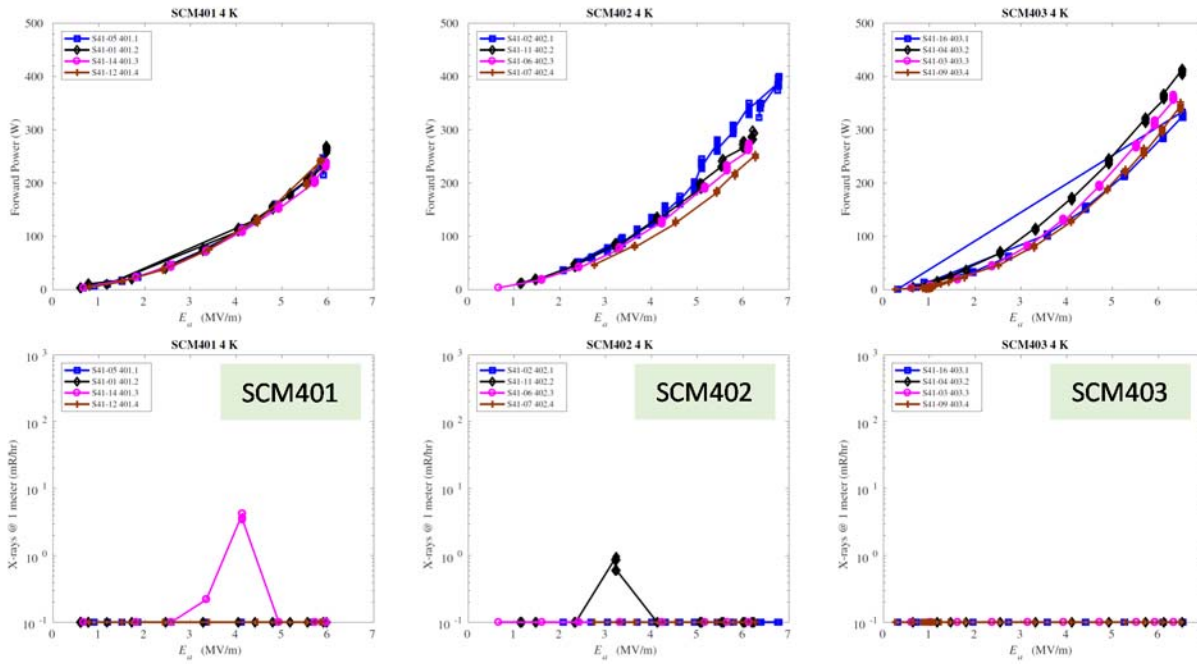

Figure 10: RF and radiation measurements at 4.3 K on β = 0.041 cryomodules.

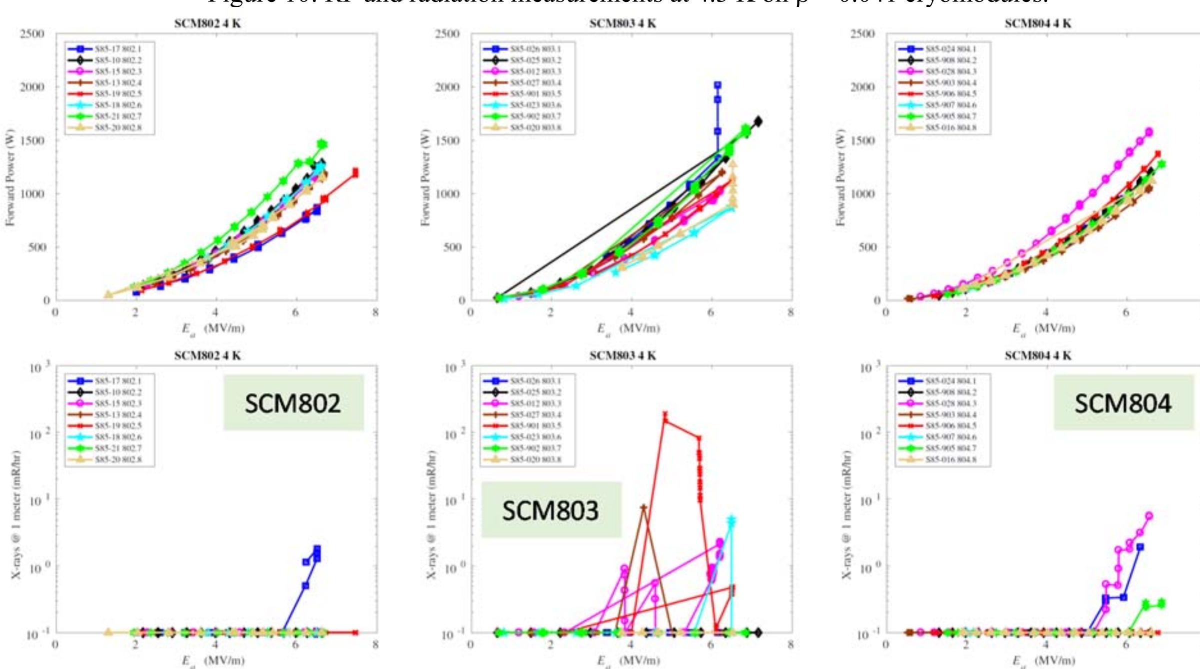

Figure 11: RF and radiation measurements at 4.3 K on production β = 0.085 cryomodules.

cavities reached E_a ~ 8.5 MV/m with RF forward power ~ 3.5 kW. There is less multipacting than we observed with pre-production couplers in the SCM501 test. The first of the MPF couplers was successfully conditioned up to 7 MV/m without DC bias, but others were more difficult to condition. As a result, we are operating all of the SCM201 couplers with the bias at present. (We plan to gather additional information to determine whether the DC bias will be needed for operation of the HWR cryomodules in the tunnel.) So far, 5 out of 6 cavities have been locked for > 1 hour at 4.3 K with E_a = 8 MV/m. The phase stability is ±1.8° and the amplitude stability is ±0.6%.

Superconducting Solenoid Packages

The FRIB accelerating cryomodules contain 1 to 3 superconducting solenoid packages for transverse focusing and steering. The first solenoid packages were Dewar tested at MSU before installation in cryomodules. Subsequent packages were tested and certified by the vendor. In the cryomodule tests, the coils are operated at full field (8 T for solenoid, and 0.06 T·m for dipoles) for ≥ 1 hour [11]. In the tests so far, the magnets operated very stably at full field without any quenches. No problems were encoun-

ISBN: 978-3-95450-191-5 doi:10.18429/JACoW-SRF2017-THYA01

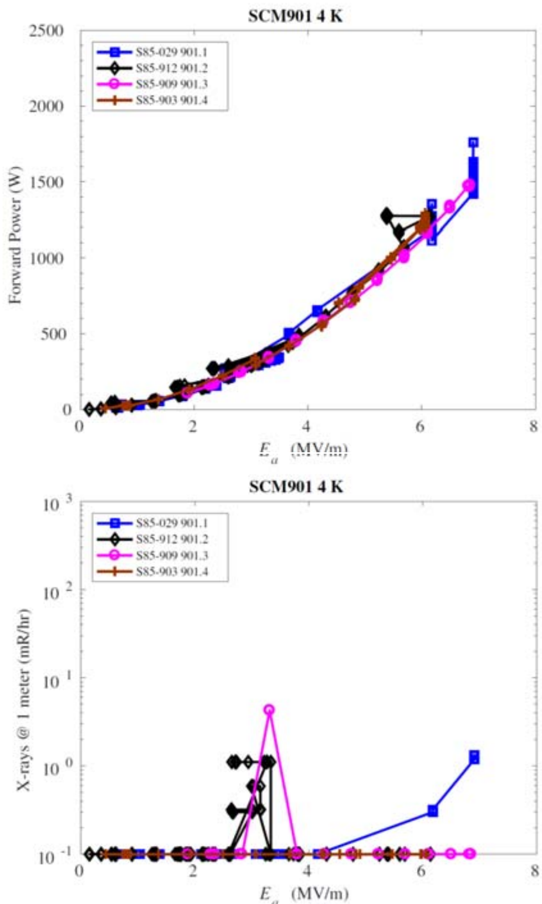

Figure 12: RF and radiation measurements at 4.3 K on β= 0.085 matching cryomodule (SCM901).

Figure 13: Cold mass for the first HWR cryomodule (SCM501).

tered with simultaneous operation of the cavities and solenoid packages. In the test of SCM501, the dynamic heat load measurement was repeated after degaussing the solenoid package and thermal cycling up to ~ 30 K. We observed no decrease in cavity Q_0 values, confirming the efficacy of the local magnetic shield design and the degaussing procedure.

SUMMARY

A total of 9 FRIB cryomodules have been tested as of July 2017. Testing of the final "first-article" cryomodule (β = 0.29) is progress. The measured dynamic loads in the cryomodule tests are consistent with expectations based on

Figure 14: Isometric view of the pneumatic tuner for β=0.53 HWRs.

Dewar testing of the cavities. The RF amplitude and phase can be controlled very well with the RF power available for cryomodule testing. Cavity preparation, cavity certification, and cryomodule certification are advancing at the expected pace and are on track for timely completion of the FRIB linac.

REFERENCES

[1] K. Saito *et al.*, "Progress of FRIB SRF Production," presented at SRF'17, Lanzhou, China, July 2017, paper TUXAA03, this conference.

[2] L. Popielarski *et al.*, "SRF Highbay Technical Infrastructure for FRIB Production at Michigan State University," in *Proc. LINAC 2014*, paper THPP046.

[3] C. Compton *et al.*, "Production Status of Superconducting Cryomodules for the Facility for Rare Isotope Beams," presented at SRF'17, Lanzhou, China, July 2017, paper FRXAA01, this conference.

[4] A. Facco *et al.*, "Faced Issues in ReA3 Quarter-Wave Resonators and their Successful Resolution," in *Proc. SRF 2013*, Paper THIOD02.

[5] K. Saito *et al.*, "Superconducting RF Development for FRIB at MSU," in *Proc. LINAC'14, paper* THIOA02.

[6] M. G. Rao, "Recent Advances in UHV Techniques for Particle Accelerators," *Proc. Int. Conf. on Vacuum Science and Technology and SRS Vacuum Systems: Indore, India, 1995* (Centre for Advanced Technology, Indore), pp. 90-104.

[7] S. Stark *et al.*, "FRIB HWR Tuner Development," in *Proc. LINAC 2016,* Paper TUPLR029.

[8] P.N. Ostroumov *et al.*, "Suppression of Multipacting in High Power RF Couplers Operating with Superconducting Cavities," *Nucl. Instrum. Methods Phys. Res. A*, vol. **856**, June 2017, pp. 77-80.

[9] Z. Zheng *et al.*, "Design and Commissioning of FRIB Multipacting-Free Fundamental Power Coupler," in *Proc. LINAC'16,* Paper THOP10.

[10] H. Ao *et al.*, "Fabrication and Cold Test Result of FRIB β = 0.53 Pre-production Cryomodule," presented at SRF'17, Lanzhou, China, July 2017, paper MOPB031, this conference.

[11] D. Luo *et al.*, "Solenoid/Magnetic Shielding Test Results in FRIB-1&2 Cryomodules," in *Proc. LINAC'16,* Paper TUPLR067.